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Research paper

Development and consideration of Chinese super-large diameter shield tunnel

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Abstract: Since the establishment of the People's Republic of China, the country has made significant progress in tunnel construction, transforming from a "weak tunnel nation" to a "strong tunnel nation." As of 2022, China has undertaken more than 60 projects involving large-diameter shield tunnels. To promote the sustainable and high-quality development of large-diameter shield tunnels in China, this article systematically reviews the development history of large-diameter shield tunnels, summarizes the current projects in the country, and addresses various aspects such as construction technology management, design technology, ecological conservation, safety, and intelligence. The article also provides suggestions for the development of large-diameter shield tunnels in China, with the aim of playing a proactive role in promoting their advancement.

Keywords: super-large diameter shield tunnel, tunnels and underground works, thinking and prospect

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1. Introduction

Transportation capacity is an important indicator of a country's economic strength, and tunnels play a crucial role in improving transportation efficiency in China. Large-diameter shield tunnels generally refer to shield tunnels with a diameter exceeding 14 m [1–4]. In 2004, the construction of China's first large-diameter shield tunnel began on Shangzhong Road in Shanghai, with a diameter of 14.87 m. As of July 14, 2022, construction of the largest diameter shield tunnel in China, the Jinan Huanggang Road Tunnel, started, with an excavation diameter of an astonishing 17.4 m [5, 6]. In less than 20 years, China's tunnel engineering has developed rapidly. By the end of 2020, China had completed 21,316 highway tunnels, with a total length of 21,999.3 km. By the end of 2021, 17,532 railway tunnels had been constructed, with a total tunnel length of up to 21,055 km [7–9]. The total length of railway tunnels is about 7,253 km, with a planned length exceeding 7,000 km. Chinese tunnels have not only achieved significant progress in terms of quantity and length but have also made great strides in construction technology, quality control, and service levels [10–13]. However, with the expansion of tunnel construction in China, foreign technological monopolies, increasing tunnel diameters, and increasingly complex engineering geology, construction risks still exist [14–18]. In order to further promote the construction and development of large-diameter shield tunnels in China, this article summarizes and organizes the current status of large-diameter shield tunnel construction in China, and reflects on the problems faced by the construction of large-diameter shield tunnels in China. It is hoped that this can play a certain role in promoting the development of large-diameter shield tunnels in China.

2. Development process of super large diameter shield tunnels in China

2.1. Initial stage of development

In January 2004, China used a large-diameter shield tunneling machine with a diameter of over 14 m for the first time in the Shanghai Shangzhong Road Tunnel project. The shield machine, manufactured by NFM company in France, was originally a Dutch Green Heart slurry balance shield machine. It had a diameter of 14.87 m and a maximum torque of 43,200 kN·m.

On September 5, 2008, the Shanghai Yangtze River Tunnel, the world's largest diameter shield tunnel at that time, was fully completed. The tunnel was excavated using two Herrenknecht-manufactured large-diameter slurry balance shield tunnel boring machines named "Changjiang No. 1" and "Changjiang No. 2," with a diameter of 15.43 m. It set the record for the longest distance achieved by a 15 m large-diameter shield tunnel at that time. The Shanghai Yangtze River Tunnel is connected to the Shanghai Yangtze River Bridge and remains one of the largest bridge-tunnel integration projects in the world to this day. The completion of the Shanghai Yangtze River Tunnel demonstrates China's determination, courage, and capability in constructing large-diameter shield tunnels. Shanghai Yangtze River Tunnel entrance is shown in Fig. 1.

Fig. 1. Shanghai Yangtze River Tunnel Entrance

2.2. Phase of independent development

Before 2008, China did not have any domestically developed tunnel boring machines (TBMs), and large-scale TBMs were completely dependent on imports. Products from Germany, Japan, and the United States occupied 90% of the domestic market. The cost of these TBMs was in the hundreds of millions of yuan, and maintenance expenses were astonishing. In 2010, when the construction of the Nanjing Yangtze River Tunnel was planned, the complex geological conditions consisting of sandstone, mudstone, and silty clay made it one of the most challenging engineering projects at that time. Not only that, but the foreign 15 m tunnel boring machine was priced at 700 million yuan, while at that time, Chinese workers were earning only a few hundred yuan. When the machine broke down, the repair costs were also borne by China, costing 3,000 US dollars per person per day, equivalent to 24,000 yuan. Moreover, during repairs, a security perimeter was established to prevent Chinese individuals from getting close. Finally, China made the determined decision to start its own research and development. In just two years, after the tireless efforts of dozens of designers, China successfully manufactured its first domestically developed tunnel boring machine with a diameter of over 14 m, known as the "Tianhe" on March 9, 2012, within the workshops of China Communications Construction Company Limited in Changshu, Jiangsu. The cost was astonishingly less than one-tenth of the imported machines. On June 22, 2015, the Nanjing Dinghuai Gate Yangtze River Tunnel was fully connected, marking the breakthrough of China's domestic large-diameter TBM and the official achievement of localization, breaking the foreign technological monopoly. Cross-section of dinghuaimen Yangtze River Tunnel in Nanjing is shown in Fig. 2.

After several years of development, domestically produced shield tunneling equipment has reached a level comparable to foreign counterparts in various aspects. The Shantou Bay Tunnel project utilized two shield machines, one imported and one domestically developed. The east line employed a German-manufactured Herrenknecht shield machine with a diameter of 15.01 m, while the west line featured the first domestically developed shield machine with a diameter exceeding 15 m. Notably, the complexity of the west line was much higher than that of the east line, posing a significant challenge to the domestically produced shield machine.

Fig. 2. Cross-section of Dinghuaimen Yangtze River Tunnel in Nanjing

In 2019, the west line tunnel achieved a daily excavation rate of 24 m and a monthly progress of 432 m, setting new records. On August 7, 2020, the west line tunnel was fully connected. In comparison, the east line took from April 2018 to May 2020 to complete. This serves as solid evidence that domestically produced large-diameter shield machines have reached international advanced levels.The successful construction of the Shantou Bay Tunnel greatly enhanced China's design, research, and application capabilities for large-diameter shield equipment under complex working conditions. It also strengthened the market competitiveness of domestically produced large-diameter shield tunneling equipment and broke the long-standing monopoly of foreign-made equipment in this sector.

2.3. Rapid development stage

Since 2015, domestically produced large-diameter shield tunnel boring machines have rapidly gained market share. As of the end of 2022, out of 68 large-diameter shield tunnel projects in China, 36 of them used domestically manufactured shield machines, accounting for 53% of the total. In 2021 and 2022, out of the 24 large-diameter shield tunnel projects initiated in China, 19 of them utilized domestically produced shield machines, reaching 79%. When Western countries monopolized the technology, the price of large-diameter shield tunnel boring machines was as high as 700 million yuan. However, after China achieved independent research and development, it dramatically reduced this exorbitant price to 25 million yuan, achieving significant cost reduction.From zero to leading-edge technology, it took only ten years for domestically manufactured large-diameter shield machines to make significant progress.

2.4. Stage of high-quality development

Over the past 20 years, China has made significant achievements in the exploration and planning, engineering design, equipment manufacturing, standards, materials, and construction technology management of large-diameter shield tunnels. On December 15, 2022, China successfully developed the first set of super-large-diameter main bearings for shield machines. The diameter of these main bearings is 8 m, weighing 41 tons, making them the largest in diameter and single heaviest main bearings manufactured in China. They will be installed on super-large shield machines with a diameter of 16 m for tunnel excavation. Chinese shield machines have evolved from being merely “made in China” to becoming a Chinese brand. In the future, domestically produced shield machines will continue to develop towards higher quality and greater intelligence. Domestic large diameter main bearing is shown in Fig. 3.

Fig. 3. Domestic large diameter main bearing

3. Statistics on large-diameter shield tunneling in China

Statistical table of Chinese super large diameter shield tunnel is shown in Table 1. A total of 68 tunnel projects are listed.

Table 1. Statistical table of Chinese super large diameter shield tunnel (Diameter > 14 m)

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
1	Shanghai Shangzhong Road Tunnel	2003	1,276+1,278	14.87	NFM	slurry balance
2	Shanghai Yangtze River Tunnel	2006	7,476 × 2	15.43	Herrenknecht	slurry balance

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Table 1 – *Continued from previous page*

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
3	Shanghai Jungong Road Tunnel	2006	1,495 × 2	14.87	NFM	slurry balance
4	Nanjing Yangtze River Tunnel	2006	3,021 × 2	14.93	Herrenknecht	slurry balance
5	Shanghai Bund Tunnel	2007	1,097	14.27	MHI	earth pressure balance
6	Hangzhou Qianjiang Tunnel	2008	3,243+3,245	15.43	Herrenknecht	slurry balance
7	Shanghai Yangtze River West Tunnel	2009	1,539+1,546	15.43	Herrenknecht	slurry balance
8	Shanghai Yingbin Third Road Tunnel	2009	1,862	14.27	MHI	slurry balance
9	Nanjing Wei San Road Tunnel	2010	4,135+3,557	14.93	CCCC	slurry balance
10	Shanghai Hongmei South Road Tunnel	2010	3,390 × 2	14.93	Herrenknecht	slurry balance
11	Yangzhou Shouxi Lake Tunnel	2011	1,278	14.93	Herrenknecht	slurry balance
12	Wuhan Yangtze River Rail and Road Tunnel	2013	2,950	15.76	Herrenknecht	slurry balance
13	Hong Kong Tuen Mun – Chek Lap Kok Tunnel	2013	800+4,200 × 2	17.63 14	Herrenknecht	slurry balance
14	Shanghai Riverside Passage Tunnel	2014	3,900	15.43	Herrenknecht	slurry balance
15	Zhuhai Maluozhou Traffic Tunnel	2014	2,840	14.93	Herrenknecht	slurry balance
16	Shanghai North Cross Passage	2014	1,910	15.56	Herrenknecht	slurry balance
17	Hong Kong Liantang Road Tunnel	2015	2,400 × 2	14.1	NHI	earth pressure balance
18	Wuhan Sanyang Road Tunnel	2015	2,590 × 2	15.76	Herrenknecht	slurry balance

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Table 1 – *Continued from previous page*

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
19	Shanghai Zhoujiazhui Road Tunnel	2015	2,572	14.90	Herrenknecht	slurry balance
20	Shantou Bay Tunnel	2015	3,037.5 × 2	15.03	CREC	slurry balance
				15.01	Herrenknecht	
21	Shanghai A30 Yangtze River Expressway Section	2016	5,090 +5, 135	15.43	Herrenknecht	slurry balance
22	Zhuhai Hengqin Tunnel	2016	1,081 +1, 082	14.90	Herrenknecht	slurry balance
23	Shanghai Chuguang Road Tunnel	2017	1,390	14.46	Herrenknecht	earth pressure balance
24	Jinan Yellow River Jiluo Road Tunnel	2017	3,526	15.76	Herrenknecht	slurry balance
25	Nanjing Heyan Road Tunnel	2017	2,970 × 2	15.01	CCCC	slurry balance
				15.07	Herrenknecht	
26	Nanjing Yangzi Fifth Bridge Tunnel	2018	1,167 +1, 159	15.43	Herrenknecht	slurry balance
27	Nanjing Yanziji Yangtze River Tunnel	2019	2,965	15.03	CCCC	slurry balance
28	Zhuhai Cross Gate Tunnel	2019	2,600	15.8	Herrenknecht	slurry balance
29	Shanghai Longshui South Road Cross-River Tunnel	2019	1,781	14.45	Herrenknecht	earth pressure balance
30	Shenzhen Chunfeng Tunnel	2019	5,080	15.8	CREC	slurry balance
31	Shanghai Yindu Road Cross-River Tunnel	2019	3,800	15.43	Herrenknecht	slurry balance
32	Hangzhou Qiantang River Cross-River Tunnel	2019	4,616	15.01	CRIG	slurry balance
33	Shanghai airports' rail link	2019	5,600	14.07	STD	slurry balance
			2,200	14.05	STD	
			4,970	14.02	CRIG	

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Table 1 – *Continued from previous page*

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
34	Shantou Bay Subsea Tunnel	2020	6,680	14.5	Herrenknecht	slurry balance
35	Wenzhou Oujiang North Entrance Tunnel	2020	2,664	14.93	Herrenknecht	slurry balance
36	Hangzhou Qinwang Passage Cross-River Tunnel	2020	1,254	15.8	Herrenknecht	slurry balance
37	Hangzhou Zhijiang Road Water Conveyance Gallery and Road Upgrading Project	2020	5,620	15.03	CREC	slurry balance
				15.01	Herrenknecht	
38	Beijing East Sixth Ring Road Renovation Project	2020	7,400	16.07	CRIG	slurry balance
					CCCC	
39	Hangzhou Xiasha Road Tunnel	2020	$1{,}485 \times 2$	15.07	CRIG	slurry balance
					Herrenknecht	
40	Jiangyin Jingjiang Yangtze River Tunnel	2020	6,400	16.06	Herrenknecht	slurry balance
				16.03	CCCC	
41	Zhuhai Tunnel	2020	5,000	15.01	CREC	slurry balance
42	Wuhan Lianghu Tunnel (East Lake Section)	2020	5,945	15.09	CREC	slurry balance
				15.07	Herrenknecht	
43	Hangzhou Genshan East Road Tunnel	2020	$3{,}160 \times 2$	15.01	CRIG	slurry balance
					Herrenknecht	
44	Shan Shan Railway Tunnel	2020	$2{,}162 \times 2$	15.01	Herrenknecht	slurry balance
45	Changsha Xiangya Road Cross-River Passage Project	2021	$1{,}500 \times 2$	15.01	CRIG	slurry balance
46	Shunde Waterway Tunnel	2021	2,230	15.56	CREC	slurry balance
47	Wuhan Heping Avenue South Extension Project	2021	2,238	16.03	Herrenknecht	slurry balance
48	Wuhu Chengnan Cross-River Tunnel	2021	$3{,}958 \times 2$	15.07	CRIG	slurry balance
				15.03	Herrenknecht	

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Table 1 – *Continued from previous page*

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
49	Nanjing Jianning West Road Cross-River Passage Project	2021	2,349 × 2	15.03	Herrenknecht	slurry balance
50	Zhanjiang Bay Subsea Tunnel	2021	9,640	14.56	Herrenknecht	slurry balance
51	Hangzhou Wenyi Road Tunnel Upgrade and Renovation Project	2021	4,060	14.17	SSG	slurry balance
52	Jinan Jiluo Road Huang Tunnel North Extension Project	2021	4,380	15.76	Herrenknecht	slurry balance
53	Guangzhou Baiyun Airport Guanghe High-Speed Rail Tunnel	2021	3,250	14.31	CREC	slurry balance
54	Guangzhou Baiyun Airport Guang'ao High-Speed Rail Tunnel	2021	3,400	14.31	CREC	slurry balance
55	Shenzhen Riverside Expressway	2021	6,400	15.4	CCCC	slurry balance
56	Zhuhai Hengqin Mangzhou Tunnel	2021	2,990	15.01	CREC	slurry balance
57	Shanghai Caobao Road Expressway Tunnel	2021	5,280	15.56	Herrenknecht	slurry balance
58	Shenzhen Huanggang Road Tunnel	2021	2,675 +1, 500	15.87	CRIG	slurry balance
59	Shenzhen Mawan Cross-Sea Tunnel	2021	2,060 × 2	15.53	CREC	slurry balance
				15.55	Herrenknecht	
60	Zhuhai Xingye Expressway (South) Tunnel	2021	1,740	15.76	CCCC	slurry balance
61	Shenzhen Wanghai Road Renovation Project	2021	7,630	16.28	CREC	slurry balance
62	Guifengshan Tunnel	2021	8,743	14.3	CREC	earth pressure balance
63	Haizhu Bay Tunnel	2021	2,077	15.07	CRIG	slurry balance

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Table 1 – *Continued from previous page*

No.	Project Name	Year	Tunnel Length/m	TBM Diameter/m	TBM Manufacturer	TBM Type
64	Wuhan Lianghu Tunnel (Nanhu Section)	2022	5,712	15.5	CCCC	slurry balance
				15.5	CREC	
65	Chongtai Yangtze River Tunnel	2022	11,325	15.34	Herrenknecht	slurry balance
66	Jihua Road West Extension Line Shunde Waterway Tunnel	2022	2,650	15.56	CREC	slurry balance
67	Haitai Yangtze River Tunnel	2022	11,185	16.6	CCCC	slurry balance
68	Jinan Yellow River Huanggang Road Tunnel	2022	4,800	17.4	CRIG	slurry balance

4. Tunnel construction challenges

4.1. Construction technology difficulties

Due to the extremely complex geological conditions faced by large-diameter shield tunneling, high construction technology requirements are necessary. Different geological conditions require different tunneling methods for shield tunnels. For example, in areas with abundant groundwater, the high water pressure in the strata weakens their strength. This can result in collapse or ground settlement during shield construction. In strata rich in organic matter, a significant amount of reinforcement material needs to be injected during shield construction to improve the foundation strength and reduce groundwater pressure. As shield construction disrupts the original geological structure, it also poses certain impacts on the safety of buildings near the tunnel.

4.2. The pressure of independent research and development

China started relatively late in the independent research and development of shield machines, and it has been limited by foreign technology. The imported main bearing for shield machines in China could only achieve a precision level of two, falling short of the level one precision machining. Therefore, achieving complete localization of shield machines has always been the most challenging step. By the end of 2022, China successfully developed an independently researched and developed main bearing for shield machines with a diameter of 8 m and weighing 41 tons, which will be installed on a super large shield machine with a diameter of 16 m. Although this is the first step for China to achieve complete independent research and development of all components for large-diameter shield machines, there is still a certain gap compared to the highest international level. The main challenge in the research and development of main bearings lies in the processing of rare earth steel in industrial production. Currently, the main bearings developed in China can achieve an operating distance of at least 10 km. The next goal for China is to exceed 30 km in length.

4.3. The awareness of shield equipment management and operational management is insufficient

At present, China has independently developed over 1,000 shield machines. The construction of tunnel projects in China is experiencing a rapid development phase, with a huge demand for construction. However, unlike foreign countries, where shield machines are designed based on the specific engineering geology and hydrogeology of each project, a single shield machine in China often serves multiple projects. This mismatch between shield equipment design and local geological conditions, as well as issues such as equipment aging, has led to many tunnel construction accidents. The management, safety regulations, and supervision measures for shield equipment in China are still not perfect.

The tunnel management methods in China mainly include the entrusted operation and maintenance mode, the market-oriented operation and maintenance mode, and the regulatory operation and maintenance mode. In comparison, the entrusted operation and maintenance mode has a high utilization rate of funds but relatively poor maintenance effectiveness. The regulatory operation and maintenance mode is the opposite, while the market-oriented operation and maintenance mode combines the advantages of both. Although China has achieved certain results in tunnel operation and management, a unified operation and maintenance mode has not yet been formed.

In addition, urban tunnels and tunnels in mountainous and aquatic areas require different management approaches due to differences in construction techniques, and specific maintenance measures need to be taken accordingly.

5. Outlook for China’s super large-diameter shield tunnels

5.1. Larger diameter

Since the 21st century, the diameter of shield tunnels in China has been continuously increasing. On September 27, 2020, the 16 m super large-diameter shield tunneling machine “Jinghua” jointly developed by China Railway Construction Heavy Industry Group and China Railway 14th Bureau Group was successfully launched. In 2021, the completely independently developed, designed, and manufactured 16.07 m slurry balance shield tunneling machine “Yunhe” had a successful maiden launch. On April 29, 2022, the 16.09 m super large-diameter slurry balance shield tunneling machine “Juli One” developed by China Communications Construction Tianhe also had a successful maiden launch. China’s self-developed shield tunneling machines continue to break through and develop towards even larger diameters.

5.2. Geological conditions becoming more complex

As large-diameter tunnel boring projects delve deeper, the range of geological formations that shield tunneling machines traverse increases, and the geological conditions become more complex. The external loads imposed on the shield tunnel lining structure will increase, and the risks associated with traversing uneven formations, such as soft and hard strata, as well as silty soils, also become greater.

5.3. Longer distances

In recent years, China has witnessed rapid growth in urban subway mileage, which has also spurred the rapid development of large-diameter shield tunnels. As of the end of 2021, the total length of operating subway lines in the country reached 4,808.3 km, accounting for 47.15% of all operating lines, surpassing the global average. On September 7, 2022, construction began on the Hai-Tai Yangtze River Tunnel, which is the longest distance, largest cross-section, and highest-speed highway underwater shield tunnel in China. It is also known as the "First Tunnel of the Ten Thousand Miles of the Yangtze River". In the future, China's large-diameter shield tunnels will continue to extend to even longer distances.

5.4. Continuous technological innovation

In 2017, China Railway Engineering Equipment Group Co., Ltd. (CREG) successfully developed the world's first shield machine with a frozen cutting head. This innovative technology involves reinforcing the outer soil layer by freezing it, creating a frozen soil curtain around the excavation face. This allows for safe and efficient cutterhead replacement under normal atmospheric pressure in complex and weak geological conditions. In the future, we can expect to see further advancements and innovations in this field.

5.5. Application of big data and intelligent technologies

In China, the construction of tunnels currently benefits greatly from the integration of "5G + intelligent + information" technologies. For example, construction personnel can wear hats equipped with positioning systems, allowing the dispatch center to remotely monitor and control them in real time. Intelligent management systems are installed inside the tunnels, enabling automatic analysis of under-excavation and over-excavation situations through 3D laser scanning and big data analysis. This improves construction efficiency and allows for monitoring of shield tunneling machine parameters, detection of toxic and harmful gases in the tunnels, and disaster early warning, among other functions.

In the future, with the emergence of higher-performance computers and technological advancements, there are tremendous prospects in areas such as geological exploration, intelligent decision-making in construction, and intelligent operation and maintenance of tunnels. These technologies will continue to advance and revolutionize the tunnel construction industry.

5.6. Safe efficient and environmentally friendly

Whether it is tunnel construction or operation and maintenance, tunnel safety always takes precedence. In the face of extreme situations, the handling and preventive measures are continuously improved, and experience is accumulated in operation and maintenance. Following safety regulations, improving emergency response plans, and further optimizing tunnel warning systems are essential.

"Clear waters and green mountains are as good as mountains of gold and silver." Strengthening cooperation with local ecological environment protection efforts, carrying out construction in accordance with the actual geological and hydrological conditions, and avoiding damage to the topography and landforms are crucial. Fully utilizing water inflows and excavated materials within the tunnel through technological means, such as converting them into construction water and building materials, turning waste into treasure, and achieving green circulation practices.

6. Conclusions

Super large diameter shield tunnel is an important part of China's urban infrastructure construction and an important direction for the development of China's tunnel technology. In the past few decades, China has made significant progress and achievements in this field. In 2022, with the successful independent research and development of the main bearing for super large diameter shield machine in China, China's self-developed super large diameter shield machine completed the last step, realizing the independent research and development and manufacturing of all components. China's shield machine has gone from following and running together to leading the world in first-class level. With the development and application of 5G technology and big data intelligence, engineering construction is more efficient and safe. By adhering to the green environmental protection ecological concept, and adhering to the safety first principle, under the main theme of striving and innovation in this era, China's super large diameter shield tunnel will develop towards larger diameter, longer distance, more efficient development, continuous innovation, and promote the development and progress of tunnel engineering in China, even the world.

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